Homer J. Fincannon

NASA Glenn Research Center

Lunar Environment and Lunar Power Needs

Lunar Environment

The lunar environment plays a large role in development of a lunar base. It affects the design of power and thermal systems. Many aspects of the lunar environment are highly location dependent, thus where a base is located is important. The primary lunar environment characteristics are summarized in the following section.

Solar illumination

For most of the lunar surface (e.g. non-polar regions), the sunlight period is ~15 days followed by a darkness period of ~15 days. For a region within 5 degrees latitude of the lunar poles, the terrain height variation results in a transition to sunlight periods of >15 days for higher terrain and <15 days for lower terrain (vice versa for the darkness periods). No sites on the Moon are 100% illuminated at or near the surface (within 1km height). Another illumination event that must be considered for base design are Earth eclipses of the Sun that can occur twice a year and last about 5 hours.

About <1% of the surface area at the poles have much longer continuous periods of sunlight and much shorter periods of continuous darkness. Due to the Sun elevation angle being relatively parallel to the lunar surface at these prime locations through the year, the illumination of at the lunar surface is problematic due to minor fluctuations of terrain (small hills, craters, rocks). However, at modest heights above the surface, better illumination is available. At 10 m above the lunar surface, from 3-4 days of maximum continuous darkness possible and over 6 months of continuous sunlight.

The time period when the average Sun elevation during a lunation is <0 degrees is termed "Winter" and >0 degrees "Summer". While the worst 'continuous darkness' is a good initial metric for selecting possible base locations, the variation of sunlight through the year for these sites shows that there is an intermittent nature to the darkness such that prior and subsequent darkness and sunlight periods must be accounted for in designs. Thus, solar power systems must to carefully designed to optimize the use of the intermittent illumination to maximize recharge capabilities to minimize energy storage mass.

Figure 1 illustrates illumination for a region in the lunar South Pole. Each square represents a terrain area of 30 m by 30 m and depicts illumination analysis results using LRO laser altimeter terrain data and a height offset from the lunar surface of 10 m (Ref. 1). This height offset is useful to avoid local shadow casting terrain and model uncertainty/error. Laser-based digital elevation models cannot capture data for the entire lunar surface (for LRO, they are limited to <7% of the surface), so the rest of the surface is interpolated (Ref. 2). Improved terrain models are required for better illumination estimates such as models derived from stereo-imagery or surface-from-shading methods. Figure 2 shows the raw illumination analysis data used to make one areal element depicted in Figure 1. The Sun appears to move around the site 360 degrees of azimuth every lunation and the Sun elevation does not vary much from 0 deg (horizontal) for the entire year. The horizon terrain mask elevation is the maximum elevation of the

entire lunar surface that is blocking the Sun at that time. The Illumination fraction is the percentage of the Sun's disc that is being blocked by the horizon terrain. The Sun diameter is 0.52 deg, thus it is a typical occurrence that it is partially blocked by the terrain.
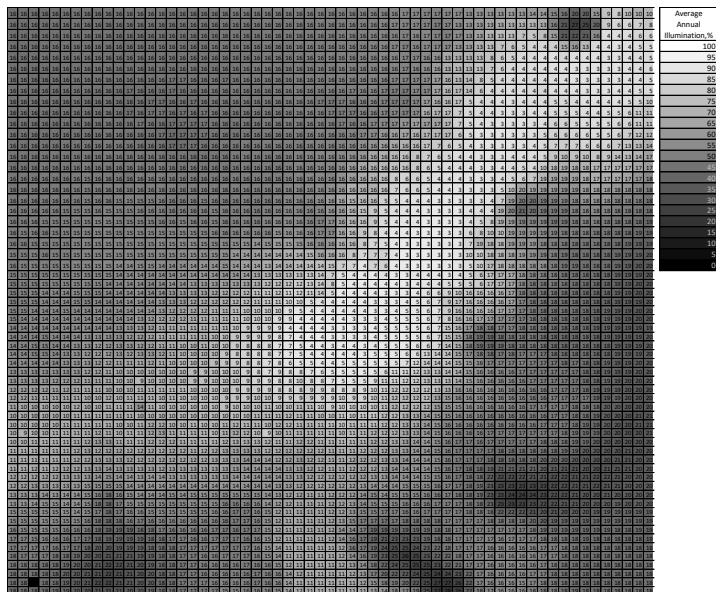

Figure 1: The longest continuous darkness period duration (in integer days) and average annual illumination (in shading) for a candidate region at the lunar South Pole.
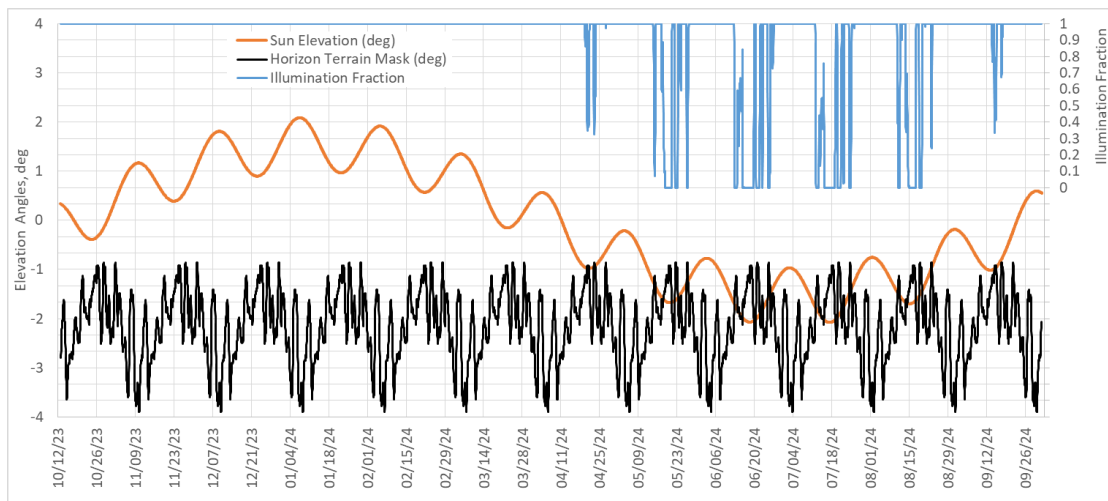

Figure 2: Illumination analysis data used to make one typical areal element in Figure 1.

Thermal

The temperature on the lunar surface varies significantly, due to the Solar illumination and the view to deep space. Candidate South Pole landing site locations experience a range from +22°C to -220°C. These are the actual regolith temperatures through Winter and Summer that lunar hardware must be designed to endure. The hardware itself will have different temperatures, likely higher, due to their

thermal characteristics and design. Polar permanently shadowed regions can go much lower than -220°C. Care must be taken in designing and testing all hardware to endure such low extremes. The non-polar lunar regions experience a more moderate range from +120°C to -130°C (Ref. 3).

Radiation

Radiation can affect the design of EVA systems, shielding of spacecraft to protect humans and electronics and degradation of materials including solar cells. The ionizing radiation experienced is similar to that seen by geostationary spacecraft (i.e. outside Van Allen radiation belts). This includes galactic cosmic radiation (GCR) and solar particle events. Solar arrays incorporate coverglasses to help protect them from solar particle radiation. GCR are difficult to protect against by shielding, but for electronics, the use of redundant systems helps to deal with the problem. Fortunately, due to the protection of the lunar surface itself the GCR problem is not as bad as on orbiting spacecraft.

Another form of radiation comes from the use of nuclear fission reactors in the base region. Such radiation is a typical byproduct of an operating reactor. This radiation can be ameliorated by a mass optimized combination of 1) distance, 2) shielding at the reactor and 3) use of terrain shielding. Typical distances used are >1 km for power transmission cables. The use of terrain to block radiation can either rely on the slope of the lunar surface to place the reactor out of the base view, burying the reactor or erecting a berm around it.

Dust

Lunar dust can adhere to various surfaces. These include solar arrays, radiators, electrical connectors, electronics as well as EVA suits, hatches and a variety of mechanisms. There are a variety of methods to ameliorate the dust problem. Either special hardware can be used such as electrodynamic dust shielding (Ref. 4) for large surfaces or the degradation can be accepted and factored into the design such as making the solar array somewhat larger because of adhered dust blocking the sunlight.

Regolith

The regolith in the Apollo landing sites have been characterized but for the region around the lunar poles, it has not been analyzed in situ. Thus, a number of properties must be determined to properly design a base. Some of these include the depth of regolith, its constituents and its mechanical/thermal properties. These affect the ability to support structures such as large landers. Also, these properties affect the issue of blast ejecta. Due to the unknown regolith depth and unknown effect of lander engines on this regolith, large quantities of dirt can be thrown at high velocities not only affecting the landing surface but also other base assets. This can be ameliorated by landing at least 1 km away from the primary base site and also at a slope tilted away from the base site (Ref. 5). It may be necessary to also reorient or retract solar arrays to minimize the effects of blast ejecta. The regolith constituent information is also useful for determination of ISRU potential of the region.

Surface slopes

It is desirable to land Elements at modest slope angles (<15 deg). However, due to accuracy of terrain data (small rocks/craters), landing gear and hardware must be designed to accommodate angles beyond this. Since solar arrays require Sun tracking, a levelling capability must be used to compensate for tilted landed spacecraft, either for the solar array or the entire vehicle. Slopes are also key for use in avoiding blast ejects and providing natural shielding for nuclear fission reactors.

Power needs

Power needs of surface elements are broad because there is a wide a range of possible mission goals for each. For rovers and mobility elements, requirements include the distance they must travel, whether they travel in total darkness and how long, what slope they must drive on, are they used for construction or regolith moving, whether they are robotic science rovers or carrying humans, whether they are pressurized or unpressurized and whether they designed to be self-sufficient in terms of energy and power or require some external support, especially for Winter darkness periods. For habitats, laboratories and other pressurized stationary assets, the size and capabilities vary similarly. The kind of ECLSS, number of supportable crew, and specific mission affects power and energy needs. For ISRU elements, the processing methods and production rates affect the power needs greatly (Ref. 6).

Nominal power level is the typical power to design a power system to. For a lunar polar base, this is when crew is present and the base is in an illumination period. Survival power levels are for the Winter dark periods when crew is absent. This power is typically for heaters to maintain hardware until nominal operation can return. Lunar polar base operation while humans are present during dark Winter periods is not allowed for various reasons. Maintaining a nominal high power level during Winter darkness drives up needed energy storage or requires power sources such as nuclear fission or RPS. Also, the very cold Winter temperatures could be hazardous to the crew should they need to perform EVAs to evacuate. Maintaining fully functioning, on-call ascent vehicles to survive Winter cold temperatures is difficult.

The following table provides a range of nominal and survival power levels for typical base elements.

Class	Element	Nominal Power, kW	Survival Power, kW
Facilities	Laboratory	4-10	0.5-2
Facilities	Habitat	4-10	0.5-2
ISRU	Demonstration	3-7	0.5-1
ISRU	Pilot	7-20	1-2
ISRU	Production	20-100	2-5
Services	Charging station	1-10	0.5-2
Rover	Robotic, small	<1	<0.2
Rover	Robotic, large	1-7	0.5-1
Rover	Human, unpressurized	1-3	0.2-0.5
Rover	Human, pressurized, small	3-7	0.5-1
Rover	Human, pressurized, large	7-20	1-3
Lander	Human, descent stage	3-7	0.5-1

Lander	Human, ascent stage	3-7	0.5-1
Lander	Robotic, small	<1	<0.2
Lander	Robotic, medium	1-3	0.2-0.5
Lander	Robotic, large	3-7	0.5-1

References:

1) 'Artemis Lunar Surface Evolution', Connolly, J., Annual Meeting of the Lunar Exploration Analysis Group, Oct 2019.
2) 'Illumination conditions of the lunar polar regions using LOLA topography', Mazarico, E, et al, Icarus 211 (2), 1066-1081.
3) 'The Global Surface Temperatures of the Moon as Measured by the Diviner Lunar Radiometer Experiment', Williams, J., et al, Icarus, Vol. 283, Feb 2017, 300-325.
4) 'Current State of the Electrodynamic Dust Shield for Mitigation', Buhler, C. R., et al., KSC-E-DAA-TN77159.
5) "Lander Plume Effects at Outpost on Shackleton Crater Rim", Metzger, P, et al, NESF2019-086.
6) "Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison", Colozza, A., NASA/CR—2020-220368.